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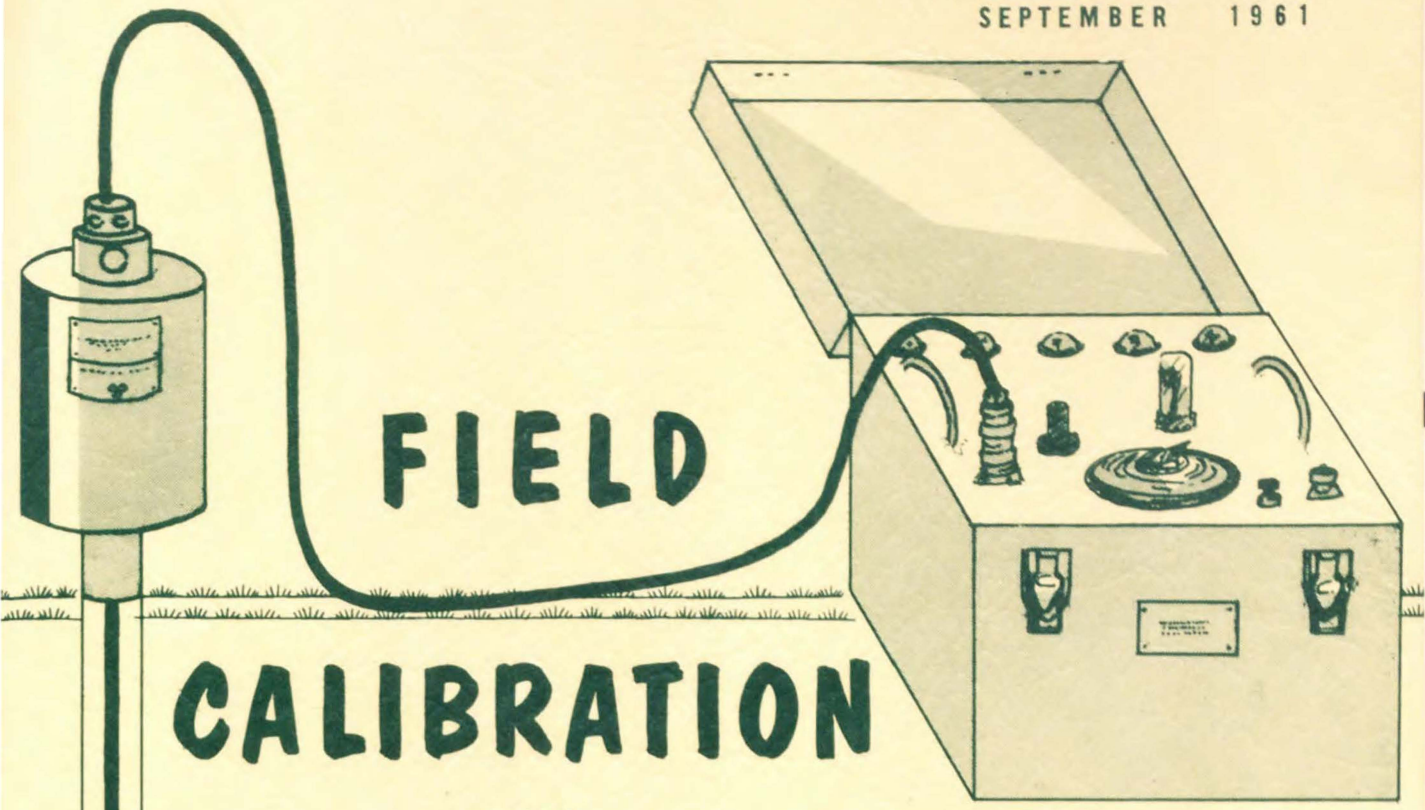

FIELD CALIBRATION OF A NEUTRON - SCATTERING SOIL MOISTURE METER

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Field Calibration of a Neutron-Scattering Soil Moisture Meter

by

Richard S. Sartz and Willie R. Curtis[1/]

The neutron method for measuring the moisture content of soils in place is now considered by many to be the most reliable method yet developed for research in plant-soil water relations. The method is not altogether new. Some of the first reports appeared in the early 1950's.[2/] [3/] Little use was made of the method, however, until more recently when a production model was developed and put on the market. Although the soil-moisture probe and scaler are now being mass-produced, the strength of the radioactive source varies slightly from one probe to another. So each must be individually calibrated by the manufacturer.

In this report results of field calibration are compared with the calibration curve furnished by the manufacturer. A method of adjusting shallow readings is also described. The instrument tested was a Nuclear-Chicago 1959 Model P-19 subsurface soil-moisture probe and Model 2800 scaler. The radioactive source is 4.61 millicuries of radium-beryllium.

The Problem

Since calibration curves are furnished by the manufacturer, one might wonder if field calibration is really necessary. Calibration procedures are cumbersome, and there may be little reason to question factory

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1/ Research Foresters, Lake States Forest Experiment Station, Forest Service, U. S. Department of Agriculture. The authors are stationed at La Crosse, Wis., where research is conducted in cooperation with the Wisconsin Conservation Department.

2/ Belcher, D. J. The measurement of soil moisture and density by neutron and gamma-ray scattering. Natl. Res. Council, Highway Res. Bd. Spec. Rpt. 2: 98-110. 1952.

3/ Gardner, Wilford, and Kirkham, Don. Determination of soil moisture by neutron scattering. Soil Sci. 73: 391-401, illus. 1952.

methods. Furthermore, Van Bavel made a strong argument against field calibration in his basic publication.[4/] He said:

> "It is very important to realize that the potential precision of the neutron method is greater than that of any other method under field conditions. It is an error to believe that the method should be calibrated in the field or 'verified' under field conditions."

He then goes on to say that, "Calibration should be carried out with large, homogeneous masses of soil of which the density and moisture content are accurately known." This last statement provokes several questions, however: How does one determine accurately the moisture content of these standards if not by gravimetric sampling? Can this be done without error? If not, calibration curves may well need further verification.

Other workers have field-tested the instrument with varying results. Merriam[5/] reported close agreement between nuclear probe, Colman units, and gravimetric samples over a moisture range of about 12 to 35 percent by volume. Marston[6/], on the other hand, using 50-gallon-drum moisture standards prepared by Agricultural Research Service personnel, Soil and Water Research Station, Coshocton, Ohio, constructed a calibration curve that differed substantially from that supplied by Nuclear-Chicago. Marston's curve showed deviations from the manufacturer's curve that ranged from plus 9 percent moisture by volume (Pv) at 36 Pv to minus 5 Pv at 10 Pv. On a straight percentage basis the former would be a difference of 25 percent, the latter a difference of 50 percent. The two curves coincided at about 24 Pv.

Field Procedure

As a result of Marston's findings, we decided to run calibration tests on our own instrument. In brief, the field procedure consisted of three steps: (1) installing moisture probe access tubes to a depth of 2 feet, (2) taking meter readings at 2-inch depth intervals, and (3) gravimetrically sampling the soil around the access tube by 3-inch layers.

4/ Van Bavel, C. H. M. Measurement of soil moisture content by the neutron method. U.S. Agr. Res. Serv. pub. ARS 41-24. 1958.

5/ Merriam, Robert A. Nuclear probe compared with other soil moisture measurement methods. U.S. Forest Serv., Pacific Southwest Forest and Range Expt. Sta., Forest Res. Note 146, 5 pp. 1959.

6/ Marston, R. B. Unpublished data. U.S. Forest Serv., Central States Forest Expt. Sta. 1960.

To check the instrument over a range of moisture contents, four calibration runs were made over a period of time. Two were made in Dubuque silt loam, a loessal soil; one in Sparta loamy fine sand; and one in undifferentiated river-bottom sand. All four profiles were free of stones.

Duplicate 2-minute readings were taken at each probe position except in the sand profile. The readings here were so low that repeat readings were not necessary. In the other three profiles the two readings usually agreed within 0.5 percent of moisture by volume.

The soil was sampled with a mallet-driven core sampler, 2-3/8 inches in diameter and 2-3/4 inches long. Volume of the sampler was 200 cubic centimeters. Every sample was a volume-weight sample as well as a moisture sample because we wanted to minimize error due to possible variation in bulk density.

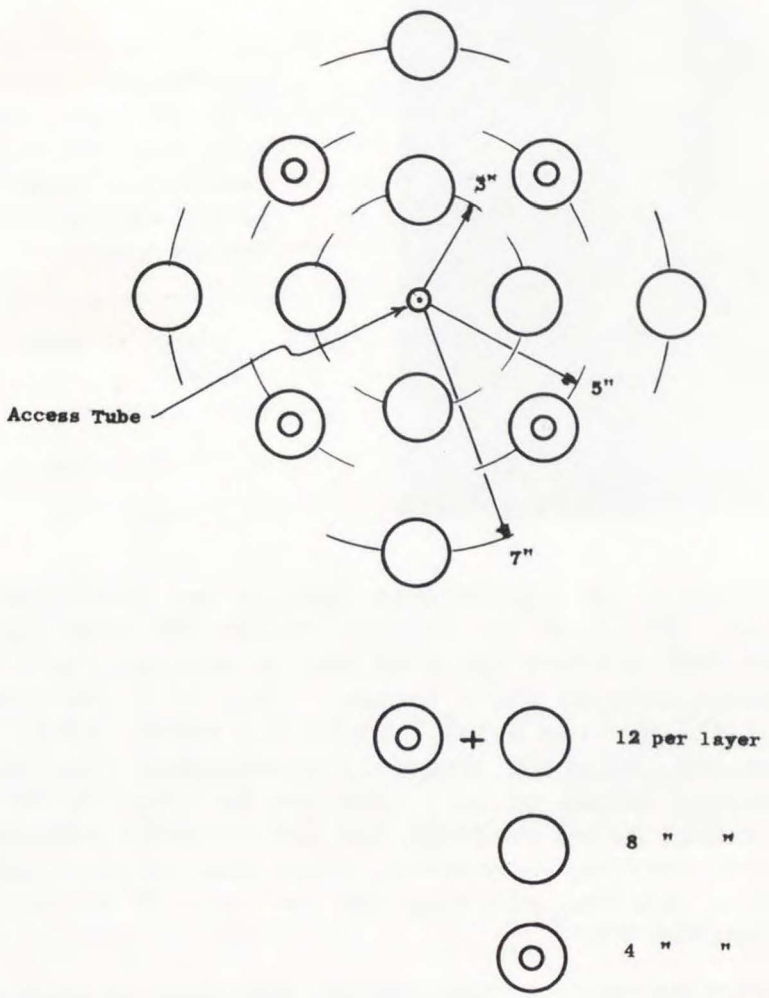

Figure 1.--Number and spacing of samples taken per 3-inch depth of profile.

The samples were taken in a spokelike design around the access tube (fig. 1). The number of samples per 3-inch layer varied from 4 to 12. (We started out by taking 12 per layer in the upper foot and 8 per layer in the lower foot, but reduced the number in subsequent plots after finding little variation.) After the last sample of a layer was taken, the top of the next layer was smoothed off. Since the core sampler was 2-3/4 inches long, it allowed 1/4 inch for smoothing between successive 3-inch layers. Sampling depth from the surface was controlled by measuring it off on the access tube as sampling progressed. Sampling down to 2 feet required excavating a pit about 5 feet in diameter (fig. 2).

Figure 2.--Removing a gravimetric sample with the core sampler. Note how the soil was removed as sampling progressed around the access tube.

Moisture content of the gravimetric samples was determined by the loss-on-drying method. Plotting the average values per sampling layer by depth showed that the vertical distribution of soil moisture was fairly uniform--at least there were no sharp breaks. This is a requirement for field calibration of the neutron meter. Since the probe "reads" a weighted average moisture content (weighted inversely by distance from the neutron source) in a much larger volume of soil than can be taken in one gravimetric sample, individual meter readings are not directly comparable to individual gravimetric readings. However, where the vertical moisture gradient is relatively uniform, plotting the two sets of values gives a good basis for comparison.

Although the first three or four readings could not be used for calibration purposes because of neutron loss to the atmosphere, we started both meter readings and gravimetric samples at the soil surface. This

was done with the hope of working out correction factors for shallow meter readings. For the same reason a second set of meter readings was taken in the second foot of soil after the first foot had been removed. The results of this will be discussed in a later section.

Calibration Results

Moisture content in the four profiles as determined by the two methods is shown by the plottings in figure 3. Gravimetric values are averages, and are plotted at the midpoint of the layer. The plotted values and number of samples per layer are given in table 1. Statistical reliability of the sample means is shown by tables 1 and 2. The neutron meter plottings are based on the manufacturer's calibration curve, adjusted for aluminum access tubes. Minor deviations in the meter plottings from the general moisture trend given by the gravimetric averages are probably due to instrument error.

Table 1.--Number of samples (n), means ($\bar{x}$), and standard errors ($s_{\bar{x}}$) for percent moisture by volume

Depth class (inches)	Pit no. 1[1]			Pit no. 2[2]			Pit no. 3[3]			Pit no. 4[4]		
	n	$\bar{x}$	$s_{\bar{x}}$	n	$\bar{x}$	$s_{\bar{x}}$	n	$\bar{x}$	$s_{\bar{x}}$	n	$\bar{x}$	$s_{\bar{x}}$
	Number	Percent moisture		Number	Percent moisture		Number	Percent moisture		Number	Percent moisture	
0 - 3	12	37.8	0.23	12	22.2	0.42	8	21.6	0.36	4	9.6	0.24
3 - 6	12	38.8	.30	12	22.9	.39	8	21.5	.20	4	12.8	.12
6 - 9	12	38.0	.02	8	25.0	.20	8	24.0	.17	4	13.1	.13
9 - 12	12	34.3	.35	8	27.0	.20	8	25.6	.29	4	13.1	.32
12 - 15	8	32.3	.36	8	26.6	.54	8	23.8	.35	4	11.4	.43
15 - 18	8	32.2	.36	8	23.6	.23	8	22.8	.20	4	8.9	.23
18 - 21	8	32.9	.47	8	24.6	.22	8	22.7	.21	4	6.1	.14
21 - 24	8	33.4	.47	8	25.5	.36	8	20.9	.37	4	5.0	.20
Average	10	35.0	-	9	24.7	-	8	22.9	-	4	10.0	-

[1] Silt loam soil, abandoned garden

[2] Silt loam soil, oak-hickory sawtimber stand

[3] Loamy fine sand, abandoned field

[4] River bottom sand, topsoil removed

Table 2.--Means ($\bar{x}$) and standard errors ($s_{\bar{x}}$) for bulk density

(Grams per cubic centimeter)

Depth class (inches)	Pit no. 1[1]		Pit no. 2[2]		Pit no. 3[3]		Pit no. 4[4]	
	$\bar{x}$	$s_{\bar{x}}$	$\bar{x}$	$s_{\bar{x}}$	$\bar{x}$	$s_{\bar{x}}$	$\bar{x}$	$s_{\bar{x}}$
0 - 3	1.08	.008	0.70	.020	1.43	.017	1.54	.010
3 - 6	1.07	.010	1.22	.027	1.56	.007	1.62	.004
6 - 9	1.26	.012	1.36	.015	1.54	.007	1.63	.005
9 - 12	1.40	.012	1.37	.013	1.40	.013	1.62	.001
12 - 15	1.44	.010	1.43	.007	1.37	.008	1.58	.008
15 - 18	1.48	.010	1.46	.011	1.38	.009	1.54	.001
18 - 21	1.54	.014	1.49	.012	1.40	.009	1.53	.018
21 - 24	1.56	.017	1.52	.013	1.47	.010	1.56	.006
Average	1.35	-	1.32	-	1.44	-	1.58	-

[1] Silt loam soil, abandoned garden

[2] Silt loam soil, oak-hickory sawtimber stand

[3] Loamy fine sand, abandoned field

[4] River bottom sand, topsoil removed

At pit 1, where gravimetric moisture was about 33 percent below the 10-inch level, meter values were consistently lower by about 3 to 4 percent moisture. In the low range (pit 4) meter values were consistently higher--from 1-1/2 percent at 13-percent moisture to about 3 percent at 5-percent moisture. The curves for pits 2 and 3 show that gravimetric and meter values coincided at the 20- to 25-percent range, but that the meter readings begin to deviate downward above 25 percent moisture.

A question frequently asked about the neutron meter is, "Are its readings affected by soil type or texture?" The results from pits 2 and 3 indicate that they are not. Moisture content was about the same at both pits, and the relationship between gravimetric and meter readings was also the same. Pit 2 was in silt loam, pit 3 in loamy fine sand of which the lower profile was coarser sand.

Assuming the gravimetric averages to be close estimates of the true mean moisture content, the meter readings at the points shown in figure 3 were plotted over moisture content as read from the gravimetric curves at the corresponding depths. By drawing a smoothed curve through these points we obtained a new calibration curve (fig. 4). The

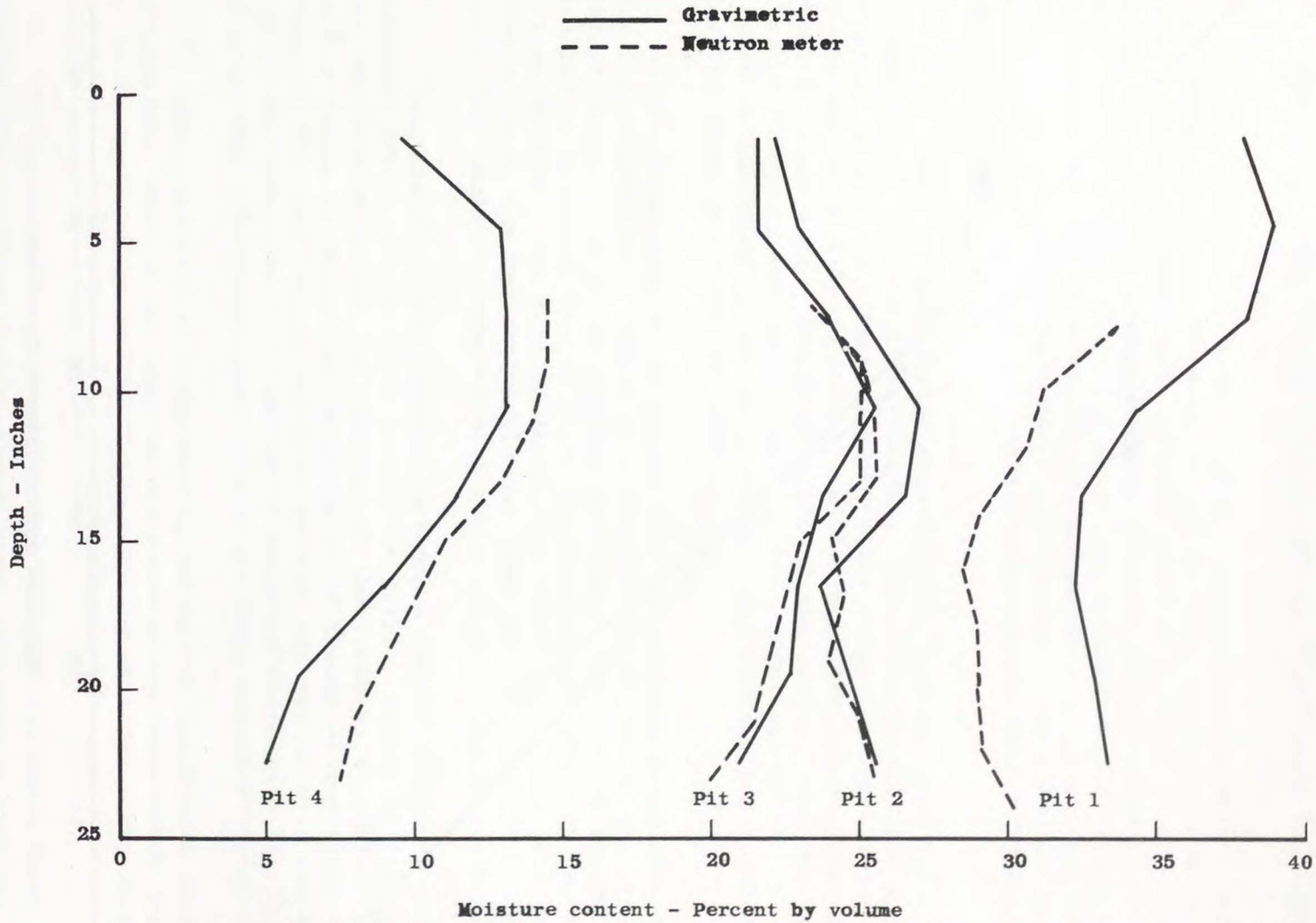

Figure 3.--Vertical distribution of moisture as measured by gravimetric sampling and factory-calibrated neutron meter. In the lower moisture range, meter values are higher than gravimetric values; at higher moisture levels, meter values are below gravimetric values.

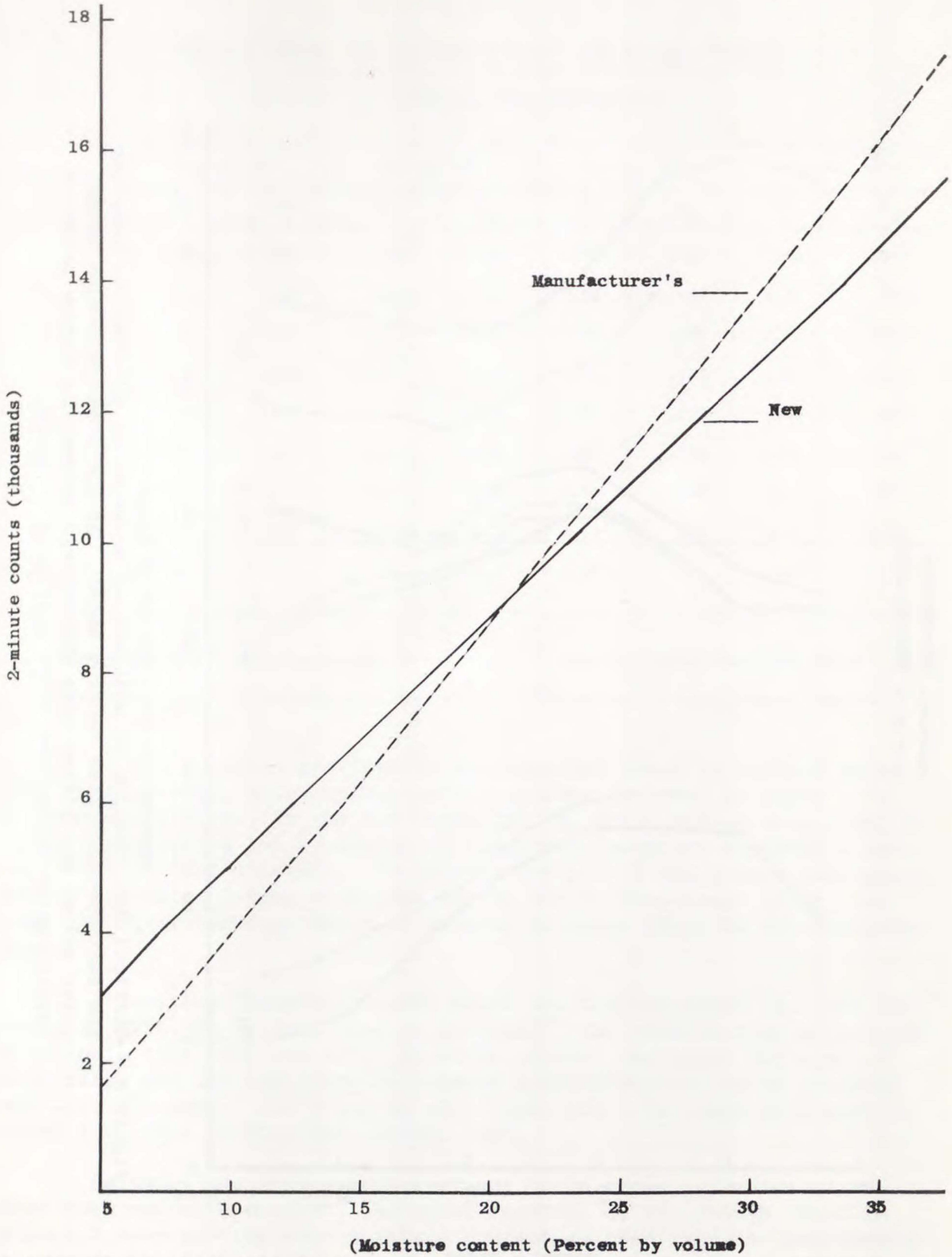

Figure 4.--Adjusted calibration curve compared with manufacturer's curve.

manufacturer's curve is shown for comparison. Deviations of the new curve from the manufacturer's agree closely with those reported by Marston.

Factory and Field Calibration Methods Compared

According to the manufacturer's instruction manual[7/], each individual probe is calibrated by establishing count rates in each of six fiber-drum calibration standards. Assumed moisture content of the standards ranges from 10.5 to 49.4 percent by volume. Moisture content of the standards was determined initially by taking neutron counts with a standard P-19 probe that had been calibrated by gravimetric sampling. Since the reliability of the manufacturer's calibration curves depends upon the accuracy of the original gravimetric sampling it seems appropriate to describe it here.

For any one calibration point, probe readings were taken at three depths: 21.5; 26.5; and 31.5 inches. Then five gravimetric samples were taken at each depth with a King tube-like sampler. The samples were evenly spaced in a 4- to 5-inch radius around the access tube, and were about 5 inches long. Inside diameter of the cutting head was 1.43 inches. Average volume of the samples was 150 cc. Total volume of soil sampled around an individual probe position was thus 750 cc; and total volume for the three positions was 2250 cc.

In comparison, if we assume that two successive 3-inch layers of the field calibration sample were roughly equivalent to the sample around one probe position in the factory procedure, the minimum volume of soil sampled at each position in field calibrating was 1600 cc, the maximum volume 4800 cc. Per foot of depth, the field sample ranged from 3200 to 9600 cc while the factory sample was 1800 cc. No sampling errors were given that could be compared with those shown in tables 1 and 2.

The field sampling system included a larger volume of soil, and extended over a greater area around the probe. Radius of influence of the radioactive source, as computed by the formula, $6(100/Pv)^{1/3}$, ranges from 8 inches at 50-percent moisture to 16 inches at 5-percent moisture. Thus, if for some reason, moisture content had varied with distance from the access tube, the field method of sampling would more likely have reflected this difference, particularly at lower moisture contents.

There was also a difference in the way in which bulk density was determined. Each of our samples was taken as an undisturbed core having a volume equal to the volume of the sampling cylinder. The manufacturer's

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7/ Nuclear-Chicago Corporation. Instruction Book, Model P-19 subsurface soil moisture probe. /n. d./

samples, which were taken with a tube sampler, varied in length, and thus in volume. Individual volumes were computed by measuring the depths of the holes from which the samples had been extracted.

Calibrating for Shallow Readings

In normal use the depth probe is not a suitable device for measuring moisture content in the soil near the surface. This is because at shallow depths the neutrons that are emitted upward from the source escape to the atmosphere. The loss varies with the moisture content of the soil above the source, and, of course, with depth. At lower moisture contents and shallower depths the loss is greater since there is less opportunity for the fast neutrons to collide with hydrogen atoms.

If one could work out corrections for shallow readings, the depth probe would give a better measure of moisture content in the upper foot of soil. We attempted to do this in conjunction with the calibration runs. Meter readings were taken at 2-inch intervals in the first 2 feet of soil, starting near the surface. (We took readings at even inches at pit 1, but switched to odd inches at later pits so that the probe would be positioned more nearly at the midpoint of the gravimetric sample.) We also made a second meter run in the lower foot of soil after the upper foot had been removed in sampling. Thus, two shallow depth runs were obtained at each pit.

The results are plotted in figure 5. In the upper foot, meter readings were compared with gravimetric values. In the lower foot, second-run meter readings were compared with first-run meter readings. This is better than the meter-to-gravimetric comparison for this purpose. All meter values were read from the new calibration curve. Because of instrument error, differences of less than one Pv are probably not meaningful. Upper-foot values for pit 2 are not shown because an error in positioning the probe made the meter readings at shallow depths unreliable.

Differences between the shallow readings and the gravimetric or meter equivalents as read from the curves in figure 5 are shown in table 3. The differences for individual runs appeared to be quite closely related to moisture content, particularly at the shallower depths; so they were grouped as shown. Group averages then, represent corrections that could be applied to shallow readings if the approximate moisture in the upper 6 inches can be estimated. From these data, it appears that an estimate within 5 Pv should be close enough for this purpose. For the moisture that we found, this estimate was given by the uncorrected reading at the 6-inch depth. One should remember that neutron loss to the atmosphere will vary with the strength of the radioactive source as well as with moisture content. The values given here are for a source of 4.61 millicuries.

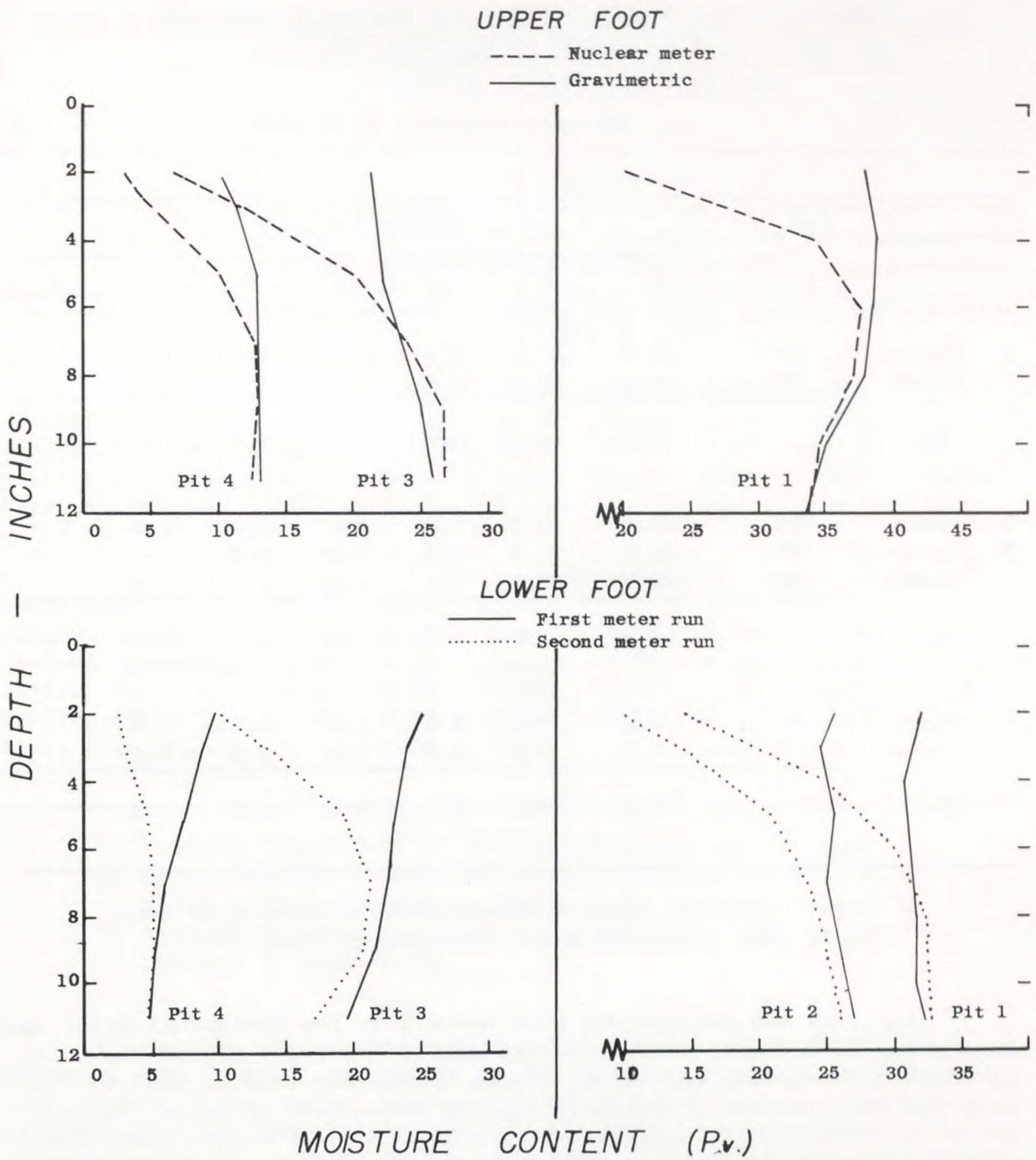

Figure 5.--Effect of probe depth on neutron meter readings. In the lower foot, the first meter run was made before the top foot of soil was removed, the second meter run after the top foot was removed.

Table 3.--Difference between shallow meter readings and actual moisture[1/]

(Percent moisture by volume)

Pit number and foot	Avg. Pv in 0 - 6"	Depth (inches)						
		2	3	4	5	6	7	8
1 Upper	38	18.0	11.0	5.0	3.0	1.0	0.5	
Lower	32	16.0	11.0	5.5	4.0	1.0	-	
Avg.		17.0	11.0	5.0	3.5	1.0	-	
2 Lower	25	15.5	10.0	7.0	4.5	3.0	1.5	1.0
3 Upper	22	14.5	9.5	5.5	2.0	0.5	-	
Lower	23	15.0	10.0	7.0	3.5	2.0	1.0	
Avg.		15.0	10.0	6.5	3.5	2.0	1.0	-
4 Upper	12	7.0	6.5	4.0	2.5	1.5	0.5	
Lower	8	7.0	5.5	4.5	3.0	2.0	1.0	
Avg.		7.0	6.0	4.0	3.0	1.5	0.5	

[1/] Actual moisture taken from gravimetric samples in upper foot, from first-run meter readings in lower foot.

Applying the corrections from table 3 to the individual meter readings gives an estimate of the average moisture content around the point at which each reading was taken. These values can then be used to estimate the total amount of moisture for the whole foot of soil. Table 4 shows the results, with gravimetric and first-run meter (in lower foot) values given for comparison. Table values are averages computed from various depth readings as shown below:

	Pit 1	Pits 2, 3, 4
2-inch intervals	2, 4, 6, 8, 10	3, 5, 7, 9, 11
4-inch "	2, 6, 10	3, 7, 11
6-inch "	6	6 (read from curve)

Table 4.--Moisture content in surface foot[1/] of soil as determined by meter readings at different depth intervals and by gravimetric sampling

Source of data	Pit number and foot						
	1		2	3		4	
	Upper	Lower	Lower	Upper	Lower	Upper	Lower
	Percent by volume						
Meter by:[2/]							
2-inch intervals	37.1	31.4	24.9	24.7	21.3	12.7	6.1
4-inch intervals	36.7	31.7	25.0	24.5	21.0	12.3	6.3
6-inch intervals	38.5	31.0	24.0	24.0	22.5	13.0	6.0
Gravimetric	37.2	32.7	25.1	23.2	22.6	12.2	7.9
First meter-run[3/]	-	31.3	25.6	-	22.1	-	6.3
	Inches of water						
Meter by:[2/]							
2-inch intervals	4.45	3.77	2.99	2.96	2.56	1.52	0.73
4-inch intervals	4.40	3.80	3.00	2.94	2.52	1.48	.76
6-inch intervals	4.62	3.72	2.88	2.88	2.70	1.56	.72
Gravimetric	4.46	3.92	3.01	2.78	2.71	1.46	.95
First meter-run[3/]	-	3.76	3.07	-	2.65	-	.76

1/ Includes lower foot of profile after removal of upper foot.
2/ Meter readings at shallow depths, adjusted by mean values shown in table 3, and averaged.
3/ Average of meter readings at 2-inch depth intervals before removal of upper foot.

Comparison of the gravimetric and first-run meter values is of interest. First meter run refers to the original readings in the lower foot of soil, i.e., before it was exposed by removal of the upper foot. So these were not "shallow readings." Assuming that the gravimetric values give the best estimate of the true soil moisture content, the differences between them and the first-run meter values are due to errors in the neutron method, not to corrections for shallow readings.

Since the corrected shallow readings in the lower foot can be directly compared with first-run meter readings taken at the same depths, the lower-foot readings provide a better measure of the reliability of the corrections. Using this basis for comparison, deviations in inches of

water in the lower foot ranged from -.09 to +.01 for 2-inch readings; from -.13 to +.04 for 4-inch readings; and from -.19 to +.05 for 6-inch readings (table 5). In comparison, the first meter-run values deviated from the gravimetric values from -.19 to +.06 inch (table 4). In other words, the deviations of the corrected values from the assumed true moisture content could be due to instrument error rather than to errors in the correction factors.

Table 5.--Deviations of corrected meter values from gravimetric values (upper foot) or from first meter-run values (lower foot)

(Inches of water)

Depth interval	Pit number and foot						
	1		2	3		4	
	Upper	Lower	Lower	Upper	Lower	Upper	Lower
2-inch	-.01	+.01	-.08	+.18	-.09	+.06	-.03
4-inch	-.06	+.04	-.07	+.16	-.13	+.02	.00
6-inch	+.16	-.04	-.19	+.10	+.05	+.10	-.04

Deviations of the corrected values from the gravimetric values in the upper foot for the respective depth intervals ranged from -.01 to +.18 inch; from -.06 to +.16 inch; and from +.10 to +.16 inch.

None of the three depth intervals appeared to give a consistently better estimate, and all values were within the expected range of instrument error. From these data, then, one meter reading at 6 inches depth was enough to measure moisture content in the surface foot. However, moisture variation was relatively small within a 1-foot layer (fig. 3). Where variation is greater, one would expect that readings at 4-inch intervals would give a better estimate. Readings at 2-inch intervals would probably never be justified.

Summary and Conclusions

A Nuclear-Chicago neutron-scattering soil-moisture depth probe was field calibrated by taking meter readings at 2-inch intervals down to 2 feet and then taking gravimetric samples around the meter access tube. After the upper foot of soil had been removed in sampling, a second meter

run was made in the lower foot of soil as a means of working out correction factors for shallow meter readings. The procedure was repeated three times. Moisture content ranged from 5 to 39 percent by volume.

It was found that the calibration curve furnished by the manufacturer gave an estimate of moisture content that was about 2 percent (by volume) higher at 10-percent moisture and 2 percent lower at 30-percent moisture. Differences increased beyond these extremes, and decreased to zero at 21 percent.

Correction factors for shallow readings were worked out that could be used to estimate moisture content in the surface foot of soil within the range of accuracy of the instrument. A single reading at 6 inches' depth gave a satisfactory estimate. However, the method should be tested further in profiles where the moisture content varies more in the 0- to 6-inch layer.

Because of the potential difference in strength of the radioactive source from one soil-moisture probe to another, the new calibration curve and the shallow-depth corrections presented in this paper are not necessarily applicable to any other probe. However, the study indicates how the instrument can be field-checked.

SOME RECENT STATION PAPERS
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